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Cheng Ying

Mariesa Crow

Missouri University of Science and Technology, crow@mst.edu

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A Diode-Clamped Multi-level Inverter For the StatCom/BESS

Ying Cheng Mariesa L. Crow
Department of Electrical and Computer Engineering
University of Missouri – Rolla, MO, 65409, USA

Abstract: Flexible AC Transmission Systems (FACTS) are potentially becoming more flexible and more economical local controllers in the power system. The integration of traditional FACTS devices with energy storage system (ESS) will increase FACTS device functionality. The voltage-sourced inverter is an important part of many FACTS devices, such as the StatCom and SSSC. Considerable research has been done on 2-level inverter usage in FACTS. Multilevel inverters, however, can improve the voltage quality and reduce the voltage stress on the power electronic devices. This paper uses a diode-clamped multilevel inverter in the StatCom/BESS. The multilevel inverter switching strategy and output voltage model are proposed. The voltage balancing issue is addressed and a circuit solution is proposed. At last, StatCom/BESS using a diode-clamped multilevel inverter is simulated in the power system.

1. Introduction

In recent years, FACTS devices have received widespread interest for high voltage power systems control. Compared with mechanically switched control of the transmission system, power electronics-based FACTS devices are faster and more flexible. The Static synchronous compensator (StatCom), based on the voltage source inverter (VSI), is a widely used FACTS device. In the StatCom, the DC side capacitor maintains the DC voltage. In this application, the DC capacitor does not need to be very large. This is different from Static Var Compensator (SVC), in which the DC side capacitors determine the controller capacity thus necessitating large DC capacitors. A StatCom controls the local voltage by injecting reactive power into the power system. However, even though both phase and magnitude of the StatCom terminal bus voltage can be dynamically controlled, they are not independent in the steady-state. The steady state PQ characteristics of a traditional StatCom are given as an arc [1] centered at $P,Q = 0$. The reactive power can be controlled flexibly within the system current or voltage limitation, whereas the active power has a very small adjustable range. In fact, the active power variation relies heavily on the StatCom losses. As a result, the traditional StatCom located in the power system can only control the reactive power and operates primarily in just two modes: inductive and capacitive.

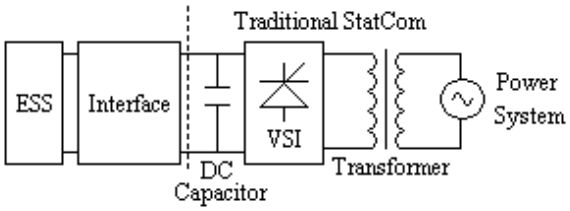

Figure 1. Simplified configuration of StatCom/ESS

An energy storage system (ESS) can play an important role in power system control. Integrating an ESS with a StatCom (StatCom/ESS) provides an improvement over traditional StatCom performance. The steady state characteristics of a StatCom with a battery energy storage system (StatCom/BESS) have been analyzed in detail [2]. In steady state, the StatCom/BESS has four operating modes and can operate at every point in the steady state characteristic circle. The circle radius is determined by the current limit. Compared with the traditional StatCom, the StatCom/BESS offers more flexibility. Considerable research has been done on StatCom/ESS with a 2-level VSI [1][2]. In a high voltage application however, a 2-level VSI will increase the cost of the StatCom/BESS due to the high voltage rating requirement for the switches. Serial connection of the switches in the 2-level VSI can solve this problem. Effective use of this structure, however, requires a simultaneous switching technique [3]. With a multilevel inverter, the voltage quality is improved, the switching frequency decreases, and the voltage stress and power losses on power devices are reduced [4]. There are normally three types of multilevel structure: the flying capacitor inverter, the cascade inverter, and the diode-clamped inverter. The diode-clamped inverter is simple and easy to control. It also has been used previously in several FACTS devices [5].

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In this paper, a diode-clamped multilevel VSI is introduced specifically for StatCom/BESS applications. First, the multilevel VSI operation modes and switching schemes are discussed. Then the imbalance phenomenon is described and a solution is proposed. Lastly, using a PSCAD/EMTDC simulation, the steady state characteristics of the multi-level StatCom/BESS is provided.

2. Diode-Clamped Multilevel Inverter Background

2.1 Main circuit

The main circuit of a 5-level diode-clamped multilevel inverter is shown in Figure 2. Normally an *n*-level diode-clamped multilevel inverter has *2(n-1)* main switches (SW1-SW4, $\overline{SW1}-\overline{SW4}$) and *2(n-1)* main diodes (D1-D8). In addition, this topology needs *2(n-2)* clamping diodes (DB1-DB6).

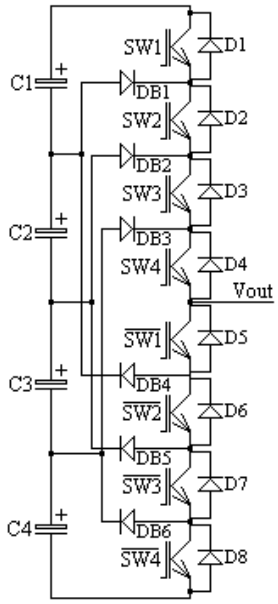


Figure 2. 5-level diode-clamped multilevel inverter

Table 1

	SW1	SW2	SW3	SW4	Vout
mode 1	on	on	on	on	2E
mode 2	off	on	on	on	E
mode 3	off	off	on	on	0
mode 4	off	off	off	on	-E
mode 5	off	off	off	off	-2E

Assuming that all DC side capacitors have the same voltage *E*, different switching modes provide different output voltages. Table 1 lists five modes for the 5-level diode-clamped multilevel inverter. The voltage V_{out} in the table is the line-to-neutral voltage. The number of inverter level comes from the voltage levels.

In every operating mode, four switches are in "on" state and the other four are in "off" state. If the inverter output voltage changes only between two contiguous modes, the main switch voltage and main diode voltage will not exceed *E* [6]. Some of the clamped diodes, however, do need to have higher rating than *E*. For example, the DB2 voltage rating should be 2E [7]. From the five modes switching operation, another advantage of multilevel inverter over the series-switches 2-level VSI is that there is no possibility of simultaneous operation of the series switches ("shoot through").

2.2 Switching strategy

The fundamental requirement for the diode-clamped multilevel inverter switching scheme is to ensure that the switches operate in the contiguous modes listed in Table 1. The most popular and simple methods are step modulation and sinusoid pulse width modulation (SPWM). In step modulation, four voltage levels are compared with the sinusoid reference waveform as shown in Figure 3. The result is used to control all the main switches.

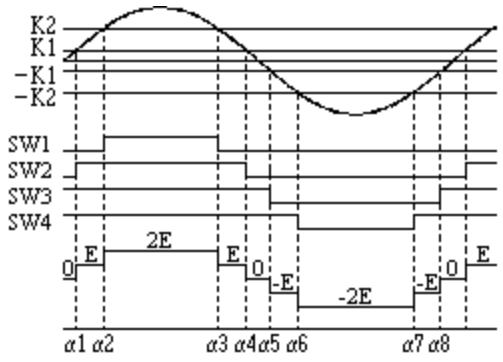


Figure 3. Step Modulation switching strategy

With Fourier transformation, the fundamental inverter output voltage magnitude can be expressed as:

$$V_{f\,max} = \frac{E}{p}\left(\int_{a_1}^{a_2} sinqdq + 2\int_{a_2}^{a_3} sinqdq + \int_{a_3}^{a_4} sinqdq - \int_{a_5}^{a_6} sinqdq - 2\int_{a_6}^{a_7} sinqdq - \int_{a7}^{a_8} sinqdq\right)$$

$$= \frac{4E}{p}(cosa_1 + cosa_2)$$

Thus,

$$V_{f\max} = \frac{4E}{p}(\sqrt{1-k1^2} + \sqrt{1-k2^2}) = \frac{4E}{p}M$$

where $M = \sqrt{1-k1^2} + \sqrt{1-k2^2}$.

The fundamental voltage is

$$V_{f\max} = \frac{4E}{p}M\cos a$$

where α is the firing angle. The analysis process is the same for 5th harmonic component, yielding

$$V_{5max} = \frac{4E}{5p}(cos5a_1 + cos5a_2)$$

In order to eliminate 5th harmonics, k_1 and k_2 should satisfy the following relation:

$$k_2 = \sqrt{1-k_1^2}\sin\frac{p}{5} + k_1\cos\frac{p}{5}$$

Then M is the function of k_1:

$$M = \sqrt{1-k_1^2} + \sqrt{1-(\sqrt{1-k_1^2}\sin\frac{p}{5} + k_1\cos\frac{p}{5})^2}$$

In SPWM, four triangular signals are compared with the sinusoid reference signal to get the switching control signal. These triangular signals are contiguous and have the same peak-to-peak value. According to different phase relationship, there are three cases: a). all triangular signals are in phase; b). the two contiguous triangular are out of phase; and c). the positive triangular signals are in phase and the negative triangular signals are in phase, but the positive and the negative are out of phase. Figure 4 shows case c.

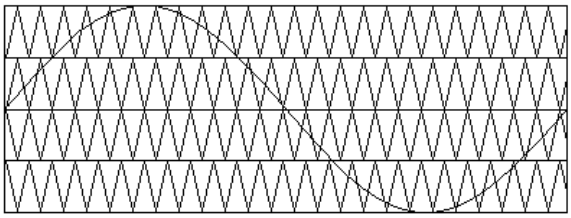


Figure 4. SPWM switching strategy

Because there are four triangular signals compared with the reference signal, the output voltage is divided into four cases. Assuming the triangular peak to peak magnitude is 0.5, then the four cases are: 0.5<d<1, 0<d<0.5, -0.5<d<0, -1<d<-0.5 (d is the reference value, i.e. specified point value of the sinusoid signal). A fast average method is used here to analyze the output voltage fundamental component [8]. Because the triangular frequency is much higher than the sinusoid frequency, the reference value can be considered as constant over small time intervals. Then the fundamental output voltage for each case is:

0.5<d<1 $V_a = E + 2(d-0.5)E = 2dE$

0<d<0.5 $V_a = 2dE$

-0.5<d<0 $V_a = -2(0.5-(d+0.5))E = 2dE$

-1<d<-0.5 $V_a = -E + (2d+1)E = 2dE$

The reference signal is $\sin wt$, thus the fundamental component of output voltage is:

$$V_f = 2E\sin wt$$

Table 2 gives the simulation voltage RMS value comparison with theoretical value for step modulation and SPWM, where M is modulation index. In step modulation, M is a function of k_1, whereas in SPWM, M is the reference sinusoid signal magnitude. The theoretical results match the simulation results closely enough for application purposes.

Table 2

Step modulation			SPWM		
M	Theoretical	Simulation	M	Theoretical	Simulation
1.3	163	160.1	0.6	118.8	118.2
1.4	176	173.5	0.7	138.6	138.2
1.5	189	182.6	0.8	158	156.1
1.6	201	196.2	0.9	178	175
1.7	214	207.2	1.0	198	193.2

3. Balancing circuit and control

Because of the different charging and discharging time of the DC side capacitors in a multilevel converter, there will significant voltage imbalance [6]. This DC side voltage imbalance will adversely affect the output voltage quality.

Voltage imbalance is an unavoidable problem for multilevel inverters. In the StatCom/ESS, this problem becomes more prevalent due to the active power exchange between the power system and the energy storage system. In order to reduce number of batteries and maximize the efficiency, just two battery sets are hooked to the 5-level diode clamped multilevel inverter. For the capacitors with batteries, the voltages can be maintained independently. But on the capacitors without batteries, the voltages will vary dramatically. The goal of the balancing control is to keep those capacitor voltages the same as the battery voltages.

Some modulation control can solve the imbalance problem. Space Vector Modulation (SVM) keeps the capacitors balanced by redundant switch modes which force current to change path as demanded. For example, as to the switching vector (E, E, 0), there are four alternative switch modes: 2E, 2E, E; E, E, 0; 0, 0, -E; -E, -E, -2E. According to the requirement of charging and discharging, any of these four modes can be chosen. But this modulation method has two

drawbacks. One is that for 5-level inverter, there are too many vectors and so the control strategy is very complicated [9]. The other disadvantage is that some vectors have only one switching mode, such as (+2E, 0, -2E), thus SVM is not suitable. Adding a DC offset to the triangular waveforms is another possible solution to correct the imbalance, but it is not fit for large modulation indices [7].

Given these constraints on switching control an additional balancing circuit is considered here. [10]. In order to simplify the neutral point imbalance, the neutral point of the DC side capacitors is connected directly to the system neutral. Now the imbalance occurs between the upper two capacitors as well as the lower two capacitors. The additional balancing circuit is shown in Figure 5. Table 3 gives the switching modes.

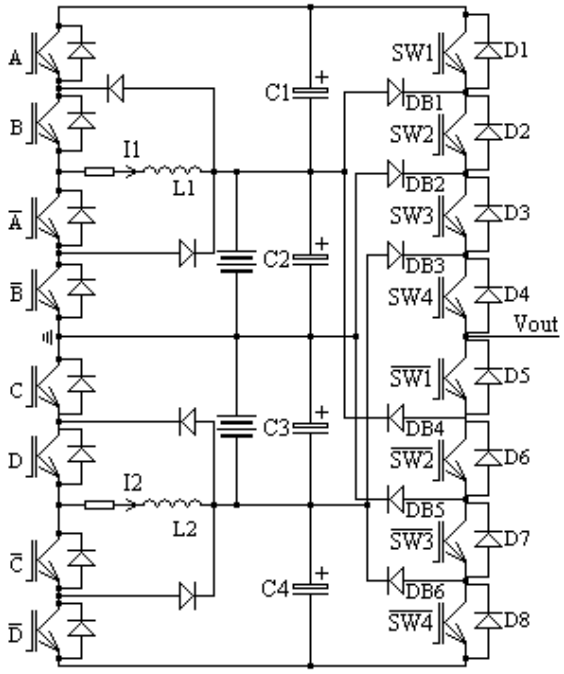


Figure 5. Balancing circuit for 5-level diode-clamped multilevel inverter

Table 3

A	B	$\bar{A}$	$\bar{B}$	Inductance current	Energy flowing
ON	ON	OFF	OFF	Negative	L1->C1
				Positive	C1->L1
OFF	ON	ON	OFF	Negative	Wheel
				Positive	Wheel
OFF	OFF	ON	ON	Negative	C2->L1
				Positive	L1->C2

In this schematic, only C2 and C3 are hooked to batteries. The voltage difference between the two capacitors can be used to control the balancing circuit switches. One battery should support both of capacitors, so the energy needs a path to flow between the battery and capacitors. Combined with proper switch operation, the inductor can act as an energy source. A small resistance is used here to absorb surplus active power and to eliminate the DC voltage offset between the two capacitors.

The non-battery capacitor voltage imbalance can be corrected by controlling it to the same as the reference voltage (battery voltage). If the voltage decreases, then the battery discharges energy to the inductor and the inductor transfers energy to the capacitor. If the voltage increases, then the capacitor discharges through the inductor and resistor pair. In fact, during a voltage drop, the balancing circuit switch states depend not only on the voltage difference between the capacitor and the battery, but also the inductor current. Assume $C1 = C2 = C3 = C4 = C$ and $L1 = L2 = L$, if C1 and C2 are not balanced, then the energy that C1 needs to maintain the reference voltage is a function of its current voltage:

$$W1 = \frac{1}{2}CE^2 - \frac{1}{2}CV_{C1}^2$$

Only when the battery has transferred sufficient energy to the inductor will the discharge stop. The inductor energy can be expressed as:

$$W2 = \frac{1}{2}LI_1^2$$

If $W1 = W2$, then the reference current is given by:

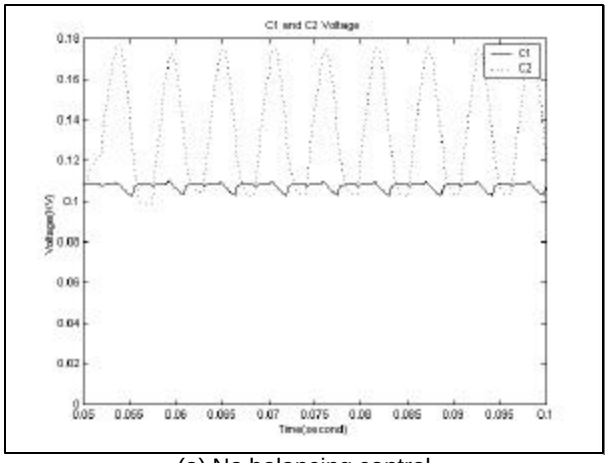
$$I_{ref} = \sqrt{\frac{C}{L}}\sqrt{E^2 - V_{C1}^2}$$

Thus, for the schematic shown in Figure 5, the switch control strategy for C1 and C2 balancing is given in Table 4:

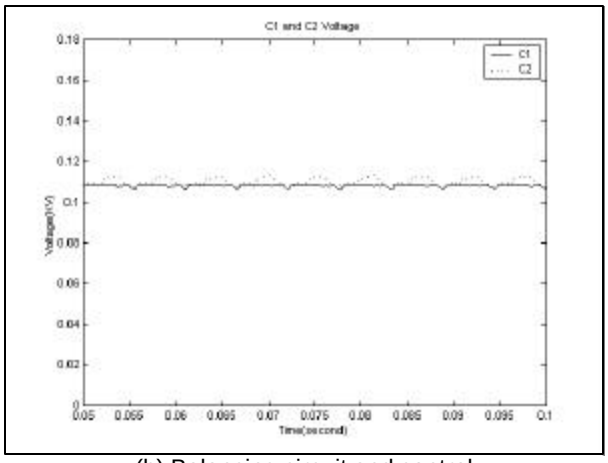
Table 4

		A	B	
V_1<E	$I_1 < -I_{ref}$	ON	ON	L1->C1
	$-I_{ref} \le I_1 < 0$	OFF	OFF	C2(battery)->L1
	$0 \le I_1$	OFF	ON	Wheel
V_1=E		OFF	ON	Wheel
V_1>E	$I_1 \le 0$	OFF	ON	Wheel
	$I_1 > 0$	ON	ON	C1->L1

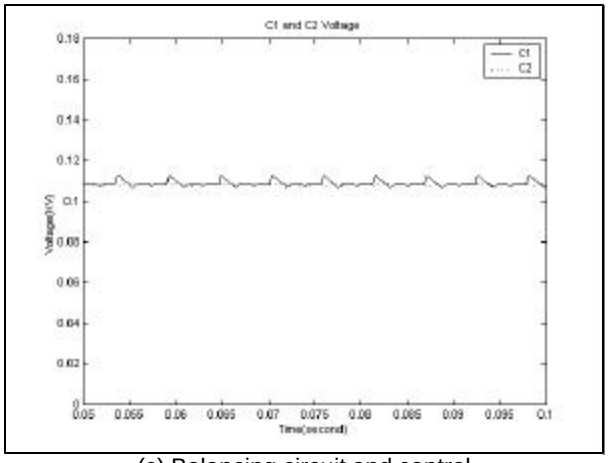
Figure 6 shows the simulated response of the balancing circuit and the control strategy. The comparison shows that a better battery location should be capacitor 1 and capacitor 4, the upper and lower capacitors.



(a) No balancing control
Batteries on C2 and C3



(b) Balancing circuit and control
Batteries on C2 and C3



(c) Balancing circuit and control
Batteries on C1 and C4

Figure 6. Balancing circuit operation

4. The Steady state simulation of the StatCom/BESS using a 5-level diode-clamped multilevel inverter

The 5-level diode-clamped inverter StatCom/BESS is simulated in a power system. Figure 7 shows the test system main circuit. The parameters Rt and Lt represent the transformer resistance and inductances and Rs and Ls represent the transmission line impedances.

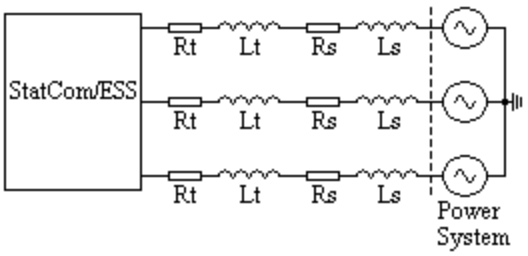


Figure 7. StatCom/BESS in power system

The system line-to-line RMS voltage is 230V, Rt = 0.06267Ω, Rs = 0.05Ω, Lt = 0.00147H, and Ls = 0.016H. This system is simulated in PSCAD/EMTDC and the steady state relationships are shown in Figure 8.

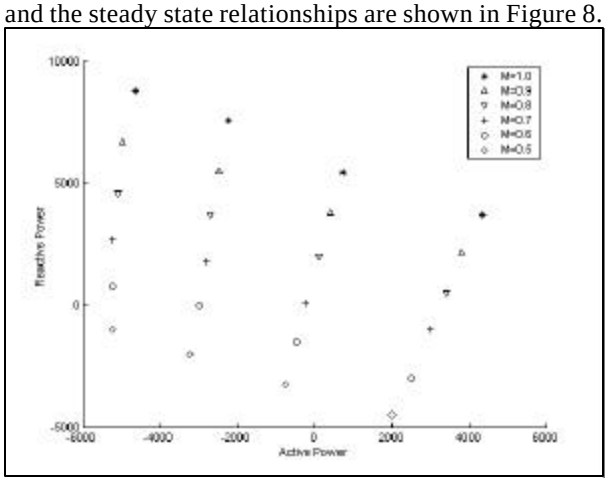


Figure 8. Steady State Characteristics of StatCom/BESS using a 5-level diode-clamped multilevel inverter

The firing angle in the simulation varies from 8^o, 4^o, 0^o, and -4^o. The modulation index varies from 0.5 to 1.0. SPWM is used in the StatCom/BESS.

Note that the active power variation depends primarily on the firing angle and the reactive power is dependent on the modulation index. This relationship can be exploited to develop a decoupled PQ control for the StatCom/BESS similar to that presented in [11].

5. Conclusions

A diode-clamped multilevel inverter can be used in the StatCom/BESS for high power applications. It has numerous advantages over a 2-level inverter, such as low switching frequency, low power device voltage rating and high voltage quality. One disadvantage of the diode-clamped inverter however, is the capacitor voltage imbalance. This imbalance can be corrected by adding a balancing circuit. Although more switches and diodes are needed, the additional circuit performs better than other balancing schemes, such as SVM and DC offset. Lately, due to the nearly linear relationship between PQ characteristics, a decoupled linear control can perform well in a diode-clamped multilevel inverter StatCom/BESS.

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